High-Frequency Acoustics of Ocean Sediments and Biot's Theory

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LONG-TERM GOALS

A physical model of high-frequency sound interaction with the seafloor including, penetration through the water-seafloor interface, as well as propagation within and scattering from the seafloor, in support of ASW and MCM applications.

OBJECTIVES

Hypotheses testing and analysis of experimental data from sandy ocean sediments to determine the underlying physical processes in the penetration and scattering of sound into sandy ocean sediments, particularly at shallow grazing angles.

APPROACH

The problem was approached from experimental and theoretical starting points. The SAX99 experiment was the main source of experimental data, but not the only source. The data analysis was directed towards determining the physical processes and mechanisms of acoustic penetration and scattering. The penetration of sound into the sediment beyond the critical angle was of particular interest. The acoustic wave speed in water-saturated sand is known to be approximately 15% greater than that of water. Consequently, there should be a critical angle beyond which negligible penetration into the sediment will occur. There have been reports from a number of at-sea (Altenburg and Chotiros, 1991; Chotiros, 1998a; Thorsos et al., 2001) and laboratory (Boyle and Chotiros, 1992; Muir, Horton and Thompson, 1979) experiments of penetration beyond the critical angle. A number of hypotheses have been advanced to explain the phenomenon. At low frequencies, typically below 10 kHz, the evanescent wave is likely to be an important mechanism, as demonstrated by Maguer, Fox, Schmidt, Pouliquen, and Bovio (1999) in a recent experiment, but this is outside the scope of the present study. The frequency band of interest in this study was the 10 to 100 kHz band. Two processes were of particular interest: penetration and scattering. There are a number of competing hypotheses for the penetration path at shallow grazing angles. The SAX99 data set directly addresses these issues.

The theoretical work was directed towards the modeling of the acoustics of sandy ocean sediments, particularly the verification of existing models to ascertain the envelope of their validity. It is common to approximate the sediment as either a uniform or layered visco-elastic fluid or a solid (e.g. Jackson and Briggs, 1992). For a fluid, the sound speed is simply related to the bulk modulus and the density. Given any two, it is possible to compute the third. The reflection coefficient at the boundary between two fluids is simply related to the ratios of the densities and sound speeds. For a solid, it is a little more complicated. In addition to the bulk modulus, there is also a shear modulus. Measurements of compressional and shear wave speeds and attenuation coefficients and the normal incidence reflection loss would be sufficient to invert for the density and the elastic moduli. However, when this approach was applied to sandy ocean sediments, the results obtained were found to be erroneous. Typically, the density and sound speed ratios are approximately 2.0 and 1.14, which gives a normal incidence reflection loss of approximately 8 dB, but the measured value is 11 dB. This discrepancy was found both in the laboratory (Nolle, Hoyer, Mifsud, Runyan, and Ward, 1963; Drevet, Brussieux and Sessarego, 1999) and at sea (Chotiros, 1995b; Jones Leslie and Barton, 1964; Dodds, 1980).

The inadequacies of visco-elastic media models generated renewed interest in poro-elastic models. A poro-elastic model, such as Biot's, is more likely to be representative of ocean sediments, because it incorporates, at least to a first order, the physics of the interaction between the solid particles and the pore fluid. Its acoustic response is represented by a pair of coupled equations of motion, one for the solid frame and the other for the pore fluid. As formulated by Stoll (1989), the model requires thirteen input parameter values, which may be divided into three groups: (1) properties of the component materials, (2) parameters related to fluid flow in the pore spaces, and (3) parameters describing the dynamic response of the frame. The parameters in the first group are well-known physical constants. Parameters in the second group include the fluid viscosity, which can be accurately measured and is tabulated for many fluids. The remaining parameters in this group are permeability, pore size and the virtual mass constant, which may be measured or estimated from fluid dynamic principles, but with less precision. The parameters in the last group are the most elusive because they cannot be directly measured and are difficult to estimate with any precision because the physics involved is not completely understood. Their values have to be adjusted to fit the measured wave speeds and attenuations. In the case of water saturated sand, there were a number of studies (Yamamoto, 1983; Stern, Bedford and Millwater, 1985; Ogushwitz, 1985; Hovem and Ingram, 1979) in the 1980s which converged on parameter values similar to those of Stoll and Kan (1981).

Biot's model, as formulated by Stoll, has been well accepted since the 1980s, but it did not completely fit experimental measurements (Chotiros, Lyons, Osler, and Pace, accepted for publication). Chotiros (1995a) put forward a set of parameter values, including a reduced value of grain bulk modulus, which predicted a slow wave speed much faster than that of the Stoll values, and which could have explained experimental observations of reflection and penetration of sound beyond the critical angle. This lead to serious discussions (Stoll, 1998; Chotiros, 1998b) and new measurements of the physical and acoustic properties of water-saturated sand. A recent acoustic measurement of the bulk modulus of sand grains (Briggs, Richardson, Williams, and Thorsos, 1999) has refuted the reduced value of grain bulk modulus, but does not explain the inconsistencies between predicted and measured acoustic properties. In this reporting period, significant progress has been made on this front.

WORK COMPLETED

An array processing method was applied to the SAX99 data. It searched through a three-dimensional space of elevation angle, wave speed and source height to detect spherical acoustic wave fronts. The method adopted is based on the simple time-delay and addition process. The time-delay beamformer is the simplest process of this type in which, given the sound speed in the medium and the array configuration, one or more planar wave fronts may be detected within a selected range of steering angles. Increasing the dimensionality of the search space by one, it is possible to search over a range of wave speeds in addition to the range of angles. In this study, the dimensionality of the search space was increased yet again, to include the curvature of the wave front, represented as the height of the apparent source position. The process is illustrated in Fig. 1.

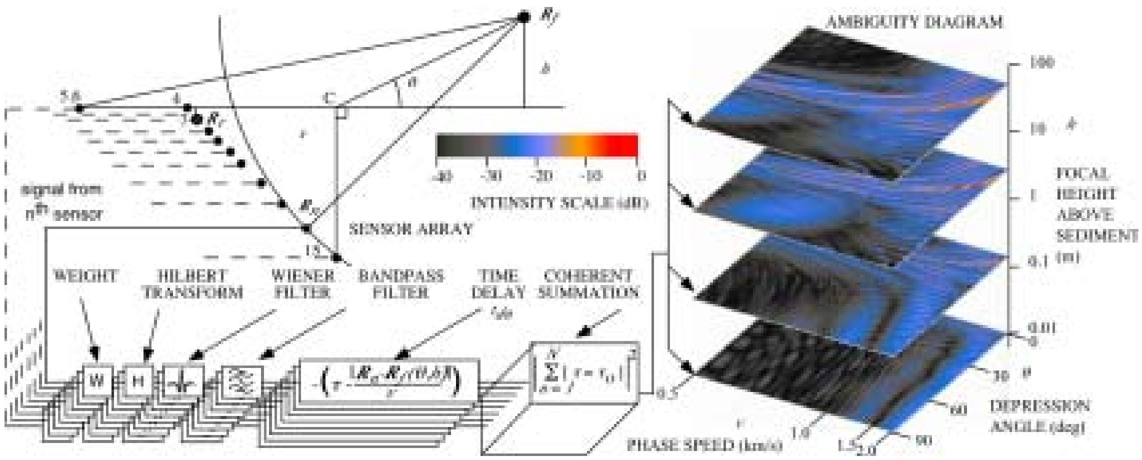

Fig. 1. Processing method for detecting and classifying sediment penetrating acoustic waves

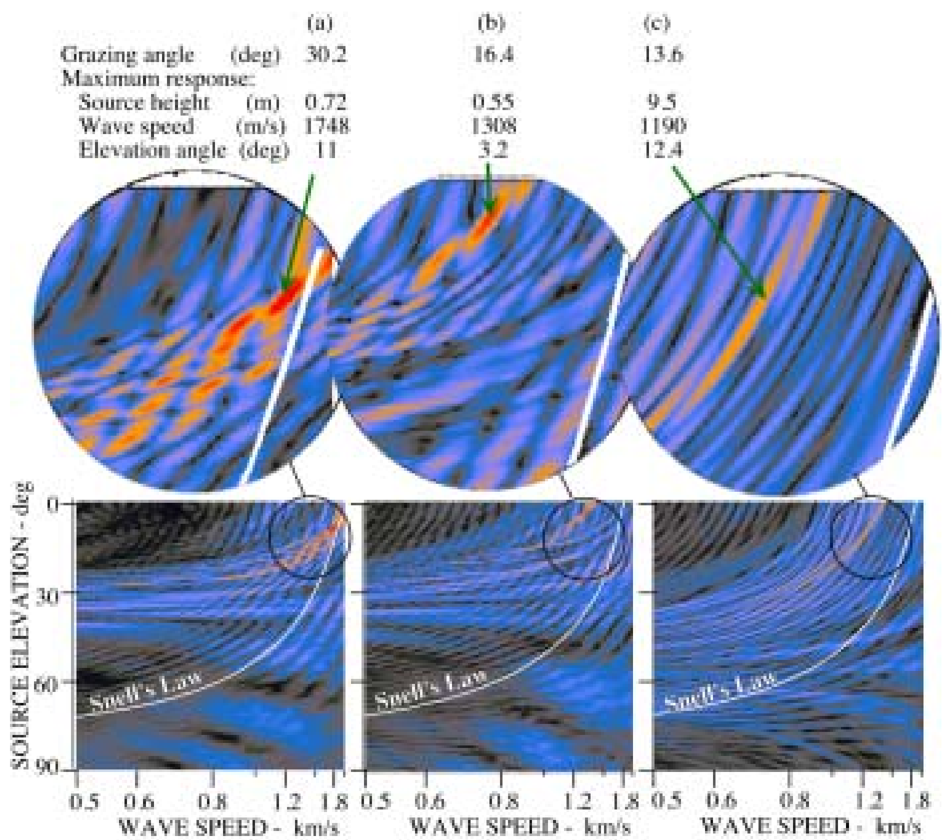

Fig. 2. Detected waves (a) above and (b,c) below the critical angle.

The output obtained is summarized in the form of horizontal slices through the global maximum as shown in Fig. 2. Three representative data sets from SAX99 are shown. (a) In the first data set, take at a grazing angle of 30.2°, which is steeper than the critical angle, there was a clear indication of a coherent wave, at a speed, direction and curvature consistent with a refracted wave obeying Snell's law. (b) In the second data set, at a grazing angle of 16.4°, which is below the critical angle, the picture was quite different. There was an indication of a coherent wave, but its position was far removed from the Snell's law curve. (c) In the third data set, at 13.2°, a weaker peak was found. In addition, there was some activity along the Snell's law curve at the lower end of the sound speed scale, in the region between 0.5 and 0.8 km/s, which suggested the presence of a second and slower wave.

With regard to model development, the inversion process developed in the previous reporting period was applied to experimental data from many sources for the purpose of extracting Biot model parameters. Three laboratory and one at-sea data sets were considered. The first and second were from measurements by Nolle, Hoyer, Mifsud, Runyan, and Ward (1963). The third was from Drevet, Brussieux and Sessarego (1999). The fourth data set was collected at sea as part of the Coastal Benthic Boundary Layer Program (CBBL), August 1993, on the West Florida sand sheet, approximately 43 km (23 nmi) southeast of Panama City, Florida (Richardson 1994). The visco-elastic model predictions were found to be inconsistent with the measured acoustic parameters of water-saturated sand. The Biot model, as formulated by Stoll in terms of 13 input parameters, fared better but there were issues related to parameter values. The model was unable to match all of the experimentally measured values of simple acoustic properties of water saturated sand, i.e wave speeds and attenuations and reflection loss at the water-sediment interface. The discrepancies lead to two hypotheses concerning the physics of grain-fluid interaction. (1) The hypothesis that the frame may contain fluid and that the pore fluid may contain loose grains was considered. This was called the composite material (CM) hypothesis. (2) The hypothesis that porosity may change as a function of fluid pressure was considered. This does not necessarily indicate a departure from isotropy or elasticity, but it does indicate that pore fluid pressure is capable of changing the frame in a way that is not compatible with the assumption of a monolithic frame structure. The rate of change of porosity is related to the coefficient of fluid content. This hypothesis was called the independent coefficient of fluid content (ICFC) hypothesis.

To further study the modeling problem, very precise laboratory measurements of reflection coefficient were made on smooth and roughened surfaces of unwashed river sand. Measurements were taken using a chirped signal from 50 kHz to 150 kHz at incident angles from 5 to 70 degrees. The roughened surface was designed to demonstrate Bragg scattering effects. Analysis of the smooth surface results will provide further testing of the above hypotheses.

RESULTS

From the analysis of the SAX99 data, sound waves penetrating the sediment may be divided into at least 4 categories. (1) Sound waves entering the sediment at grazing angles greater than the critical angle are mainly refracted, identified by high coherence and adherence to Snell's law. (2) As the grazing angle approaches the critical value, the refraction process appeared to make a smooth transition into a scattering process. As the grazing angle value drops below the critical value, there is a departure from Snell's law and the apparent wave speed is less than the intrinsic wave speed of the medium but the wave is still remarkably coherent. It was likely a scattered wave of the type described by Thorsos, Jackson and Williams (2000). (3) As the grazing angle is reduced further, the coherence of the scattered wave is reduced. (4) In addition, a second refracted wave in the 500 to 1000 m/s speed range was suggested by the pressure ridges that intersect the Snell's law curve in the lower part of Fig. 2(c). Simulations showed that the width and orientation of the ridges are consistent with one or more refracted slow waves. This is a tentative result that requires further investigation.

Model-experiment comparisons showed that the poro-elastic model is superior to visco-elastic models. Residual differences remain and new hypotheses (CM and ICFC) are being developed to overcome them. Both hypotheses are feasible. Furthermore, the two hypotheses are not mutually exclusive.

IMPACT/APPLICATIONS

The acoustic penetration path above the critical grazing angle is clearly understood in terms of refraction. The path or paths beyond the grazing angle may not follow Snell's law. The measurements by Thorsos and his colleagues at APL/UW, using a sound path that was perpendicular to the sand ripples, detected an acoustic wave with an apparent speed faster than that of the known sound speed in the sediment. The measurements reported here, using a path parallel to the ripples, indicated a wave with an apparent speed that was much slower. Neither wave obeyed Snell's law, but they likely represent similar scattering paths. These results will lead to improved models of sediment acoustic interactions.

The inversion results show that sandy ocean sediments cannot be accurately represented as visco-elastic media. Poro-elastic models are better, but need to be improved to account for significant residual discrepancies. These results will have a significant impact on the modeling of ocean acoustics in littoral waters. All of the current standard acoustic propagation and scattering models that have been accepted and certified by the Navy's Ocean Acoustic Mathematical Library (OAML) approximate the ocean sediment as a visco-elastic medium. While the main theater of operations was in blue waters, where bottom interactions were very minimal, this was adequate, but in littoral waters its deficiencies become very apparent. The results obtained point the way toward more accurate models for sediment acoustic interactions that will be needed for ASW applications in the littorals, and for the modeling of buried mine detection in MCM applications.

TRANSITIONS

The results provided a theoretical framework for analyzing bottom reverberation data currently being collected under NAVO sponsorship contract N00039-96-D-0051-1-88-1, and sonar performance predictions sponsored by ONR code 322 under contract N00039-96-D-0051-1-82-1. They will form the basis of future models of acoustic buried mine detection and imaging, and shallow-water propagation.

RELATED PROJECTS

This project is tightly coupled to the other projects under the ONR "High-Frequency Sediment Acoustics" DRI, since the environmental inputs required for analysis are dependent on other projects within the DRI, and to parallel experiments conducted by the Naval Research Laboratory (NRL). The project is benefiting from data exchanges with the Acoustic Penetration Experiment (APEx) of the SACLANTCEN, in Italy, on a similar sandy sediment in the Mediterranean. Laboratory studies by the LMA, under the sponsorship of the Groupe d'Etude Sous-Marine d'Atlantique (GESMA), France, are producing complementary measurements, and GESMA has expressed an interest in having similar sediment penetration measurements made on the French coast. Finally, collaboration was established with a study of the changes in the abundance and distribution of Pacific Northwest estuarine keystone species in response to multiple abiotic stressors, within the Western Ecology Division of the U.S. Environmental Protection Agency.

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